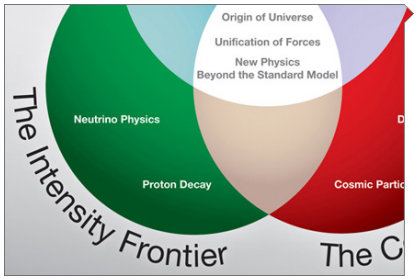

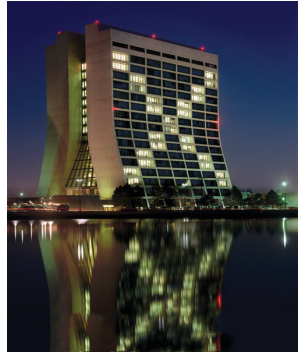

N-N-bar Oscillation and Physics Beyond standard model

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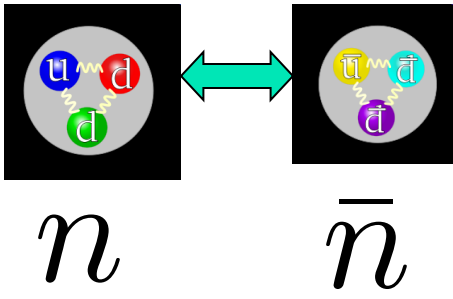
What is N-Nbar oscillation ?

- **Neutrons in vacuum and low magnetic field spontaneously converting to anti-neutron.**
- Free oscillation time $\tau_{n\bar{n}} = \dfrac{\hbar}{\delta m_{n\bar{n}}}$



- Transition probability: $P_{n\to\bar{n}} \approx \left(\dfrac{t}{\tau_{n\bar{n}}}\right)^2$
- # of events: N $P_{n\to\bar{n}}$ x running time (N=neutron flux)
- Current direct search limit ILL $\tau > 8.6\times10^{7}$ sec
- → $\delta m_{n\bar{n}} < 10^{-32} GeV$
- $\tau_{n\bar{n}}$ can be probed up to $10^{10\text{-}11}$ sec. (Kamyshkov and Snow's talk)
- $\delta m_{n\bar{n}}$ is the particle physics probe !!

Given this limit on $\tau_{n\bar{n}}$ why are nuclei stable ?

- Oscillation inside nuclei are suppressed by the factor $\left(\frac{\delta m_{n\bar{n}}}{V_n - V_{\bar{n}}}\right)^2 \leq 10^{-62}$
- More detailed calculation: (Dover, Gal, Richard; Vainstein's talk)

$$\tau_{Nuc} = R\tau_{n\bar{n}}^2 \quad R = 0.3\times10^{23}\ \text{sec}^{-1} \rightarrow \tau_{Nuc} \geq 10^{32} yrs$$

- Super-K search (Kearns' talk) $\tau_{n\bar{n}} > 2.44\text{x}10^8$ sec.

Why is it important to search for NNbar ?

- Many reasons to believe that **baryon number (B) is not a good symmetry of nature** :

Sphalerons in SM , GUTs, origin of matter etc.

- If B is violated, important to determine the selection rules: B=1 (p-decay) or B=2 (NNbar) ?

i) What is the scale at which B- symmetry is broken ?

NNbar → lower scale physics than usual p-decay

ii) NNbar oscillation intimately connected to neutrino mass physics when combined with quark-lepton unification

(i) Operator analysis and scale reach of NNbar

SM particles $O_{\Delta B=2} = \frac{1}{M^5} u^c d^c d^c u^c d^c d^c$ **d=9**

Note M^5 suppression

$\delta m_{n-\bar{n}} = O_{\Delta B=2} \Lambda_{QCD}^{\ 6}$ (Lattice talks)

$\tau_{n-\bar{n}} = \hbar / \delta m_{n-\bar{n}} \sim M^5 / \Lambda^6 \rightarrow \tau_{n\bar{n}} \sim 10^8 s.\ M \approx 10^{5.5} GeV$

TeV diquarks: $\rightarrow \Delta_{u^c d^c} \rightarrow \frac{1}{M} d^c d^c \Delta_{u^c d^c} \Delta_{u^c d^c}$

Probe M_{B-L} to 10^{15} GeV

P-decay $\rightarrow \frac{1}{M^2} QQQL$

$M \geq 10^{15}\ GeV$

(ii) Neutrino mass NNbar connection

- SM has exact global B-L symmetry !!
- If neutrino is Majorana fermion, it breaks **L**-part of **B-L**
- observation of $\beta\beta_{0\nu}$ decay will be a significant discovery which will confirm this but will not tell us much about associated new physics.
- N-N-bar oscillation breaks B-part of B-L and provide complementary information-

  e.g. if NN-bar is observed, either all or surely some of nu-mass physics is at the TeV scale and will be accessible in other expts e.g. LHC, FCNC, edm

Questions for N-N-bar oscillation

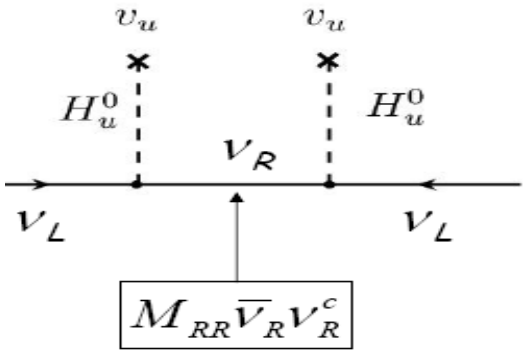
- Are there decent (predictive?)theories explaining small neutrino masses which give observable N-N-bar oscillation ?
- Implications of observable N-N-bar for cosmology i.e. does it affect conventional explanations of origin of matter/can it explain itself ?
- Two examples of models for NNbar:

(i) **TeV scale Seesaw +Quark-Lepton unif.**

(ii) **SO(10) GUT scale seesaw+TeV sextets**

Majorana neutrino mass via seesaw and NNbar

- SM+ right handed neutrinos N_R with Majorana mass $(B-L)$



$$m_\nu \cong -\frac{h_\nu^{\,2} v_{wk}^{\,2}}{M_R}$$

Minkowsk'77i; Gell-Mann, Ramond, Slansky; Yanagida; Glashow, Mohapatra, Senjanovic'79

- $M_R << M_{Pl}$ →B-L a gauge symmetry→N Majorana mass arises from a new Higgs vev $< \Delta_R >$ (like SM fermion masses from <H>):
- What is $< \Delta_R >$, the actual scale of B-L breaking ?
- Do quarks and leptons unify to big picture of flavor ?
- NNbar search can answer these questions !!

A unified TeV scale embedding of seesaw

- If Q-L unified at the seesaw, a model is

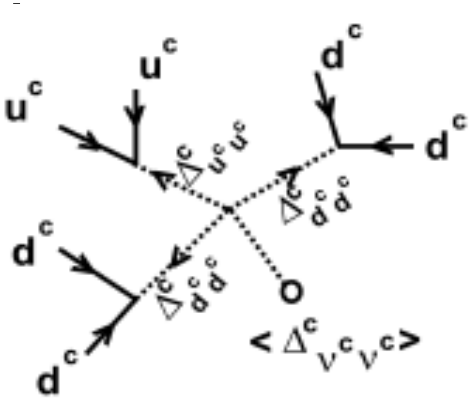
$$SU(2)_L \times SU(2)_R \times SU(4)_c \begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R}$$

→SU(4) generalization of the seesaw Higgs field Δ_R has partners Δ_{qq} connecting to qua

→N-N-bar Feynman graph;

(Mohapatra,Marshak'80)

→No proton decay.



- Colored seesaw partners at TeV scale→ $\tau \sim 10^{10-11}$ sec.

Low scale NNbar model and origin of matter

- Only constraint on model is from nu masses. Without additional assumption, this model cannot predict $\tau_{n\bar{n}}$
- Assumption of low scale baryogenesis puts constraints on the $SU(2)_L xSU(2)_R xSU(4)_c$ model parameters and makes a prediction: (Babu's talk 6/16)
- For a B-L scale < 50 TeV, the constraints put an upper bound NNbar transition time < 10^{11} sec.
- **No NNbar till 10^{11} s., will rule out this model for post sphaleron baryogenesis if v_{BL} < 50 TeV**

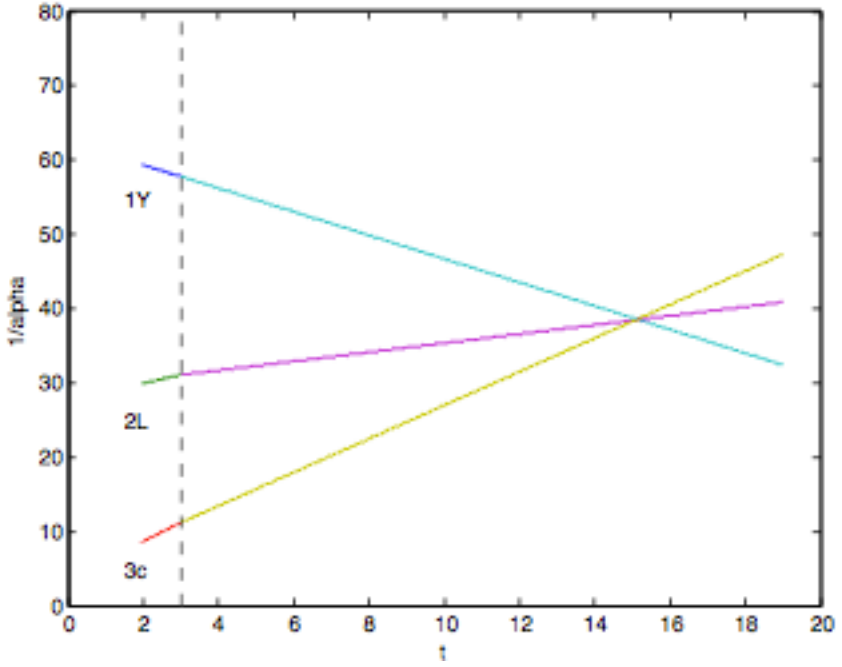
(Babu,Dev,RNM'PRD'09)

Seesaw in SO(10) –Another predictive model for NNbar

- Coupling unification fixes the mass scales as in the case of proton decay:
- In a minimal SO(10) embedding of seesaw, f_{ab} determined from fermion mass fits
- (Babu, Mohapatra'93; Fukuyama, Okada'02; Bajc, Senjanovic, Vissani'02; Goh, Mohapatra, Ng'03 Babu,Macesanu'05; Bertolini, Malinsky,Schwetz'06; Joshipura, Patel'11)
- Predicts correct θ_{23}, θ_{12} and $\sin^2 2\theta_{13} \simeq 0.09$
- Model has diquarks at sub-TeV scale to have unification and they lead to observable NNbar !

New Unification profile

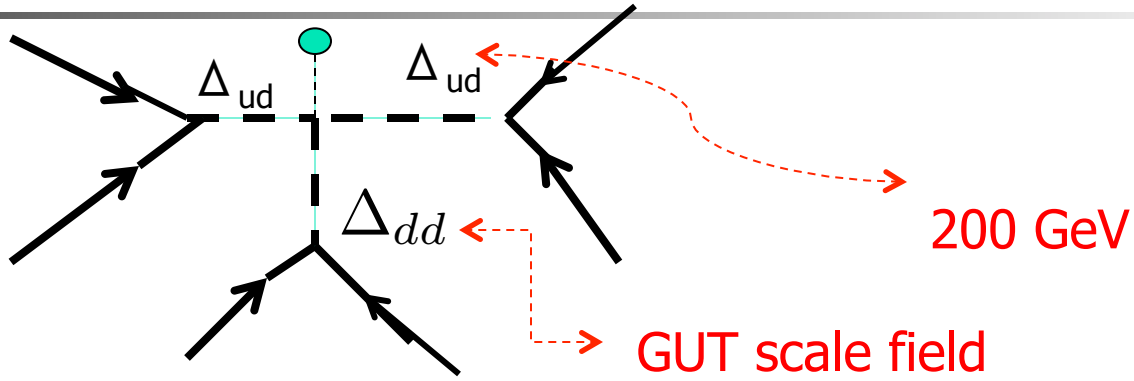
- Non-SUSY SO(10) does not unify without low scale particles,
- Coupling unif with sub-TeV $\Delta_{ud}(6,1,\frac{1}{3})$ + 2 SM triplets+2 Higgs;
- Predicts seesaw scale near $M_U \sim 10^{16}$ GeV;
- Δ_{ud} mass ~2 TeV
- $M_U \sim 10^{15.7}$ GeV→ $\tau_{p\to e^+ + \pi^0} \simeq 3.2 \times 10^{34} yrs$ close to current limit.



(Babu, Mohapatra, arXiv:1206.xxxx)

Estimate of N-N-bar oscillation time

- Diagram:



- $$G_{\Delta B=2} \simeq \frac{\lambda f_{11}^3 \eta^3}{\lambda' M_U M_{\Delta_{ud}}^4} \simeq \frac{\lambda}{\lambda'} 10^{-33} GeV^{-5}$$
- Predicts $\tau_{n-\bar{n}}$ ~10^{10} -10^{13} sec.
- Constraints of adequate baryogenesis enhances this to $\tau_{n-\bar{n}}$ ~10^{8} -10^{11} sec.

New Particles at LHC: Color sextet scalars Δ_{qq}

- TeVColor sextets are an inherent part of both models ; Can be searched at LHC:

(I) **Single production**: $ud \rightarrow \Delta_{ud} \rightarrow tj$

xsection calculated in **(RNM, Okada, Yu' 07;)** resonance peaks above SM background- decay to tj;

- **Important LHC signature:** $\sigma(tt) > \sigma(\bar{t}\bar{t})$

(II) **Drell-Yan pair production** $q\bar{q} \rightarrow G \rightarrow \Delta_{ud}\bar{\Delta}_{ud}$

- Leads to $tjtj$ final states: **LHC reach < TeV**

(Chen, Rentala, Wang; Berger, Cao, Chen, Shaughnessy, Zhang' 10; Han, Lewis' 09)

Origin of matter and neutron oscillation

- Current scenarios:

(i) Leptogenesis; Related to seesaw; but hard to test !

(ii) Electroweak baryogenesis :

M_{higgs} <127 GeV; $m_{\tilde{t}} \leq 120 GeV$ (puts MSSM under tension)

- New scenarios: (Babu's talk)

(iii) Post sphaleron Baryogenesis } both connected

(iv) GUT baryogenesis } to NNbar osc.

- Non-observation of NNbar upto 10^{11} sec.will rule out simple models for PSB as well as the particular SO(10) model.

Benchmark goal for ruling out new physics scenarios

- **No NNbar oscillation till 10^{11} sec. →**

★ Will rule out a class of SU(2)xSU(2)xSU(4)$_C$ models for post sphaleron baryogenesis (perhaps even a larger class class of models) !!

★ Will rule out a sub-class of non-susy SO(10) models for neutrino masses that predicted recently observed large θ_{13} if it is to explain the origin of matter.

Implications of NNbar observation for low energy

- FCNC effects in the B and D-sector: could reconcile anomalies e.g. $\epsilon_K \ vs \ \sin 2\beta$, B-decays etc.

- EDM of neutron from PSB→ non-zero at two loop

- Strange dibaryon decay: NN→ KK+X **(Glashow)**

  Mediated only by $\Delta_{ud.dd}$: Related to $\Lambda - \bar{\Lambda}$ transition

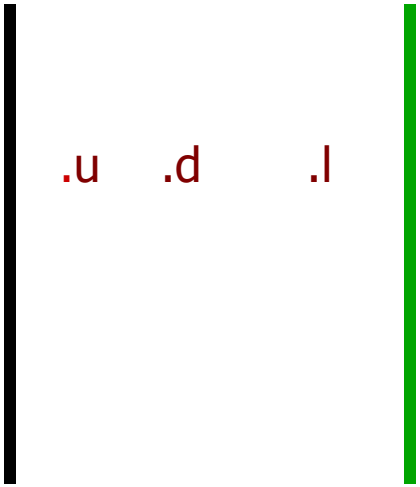
  $\tau_{Nuc} = R\tau^2_{free}$ formula implies: $\tau_{KK} \sim 10^{34} - 10^{35} yrs$

  Current Super -K upper limit: >1.7x10^{32} yrs.

Other theories for NN-bar

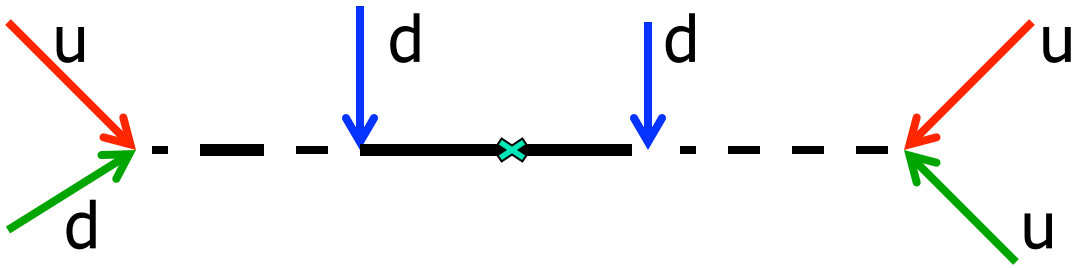
- TeV scale extra Dim models:

Dvali, Gabadadze; J. N. Ng, Winslow;
Nussinov, Shrock



- Gluino graphs in GUTs:

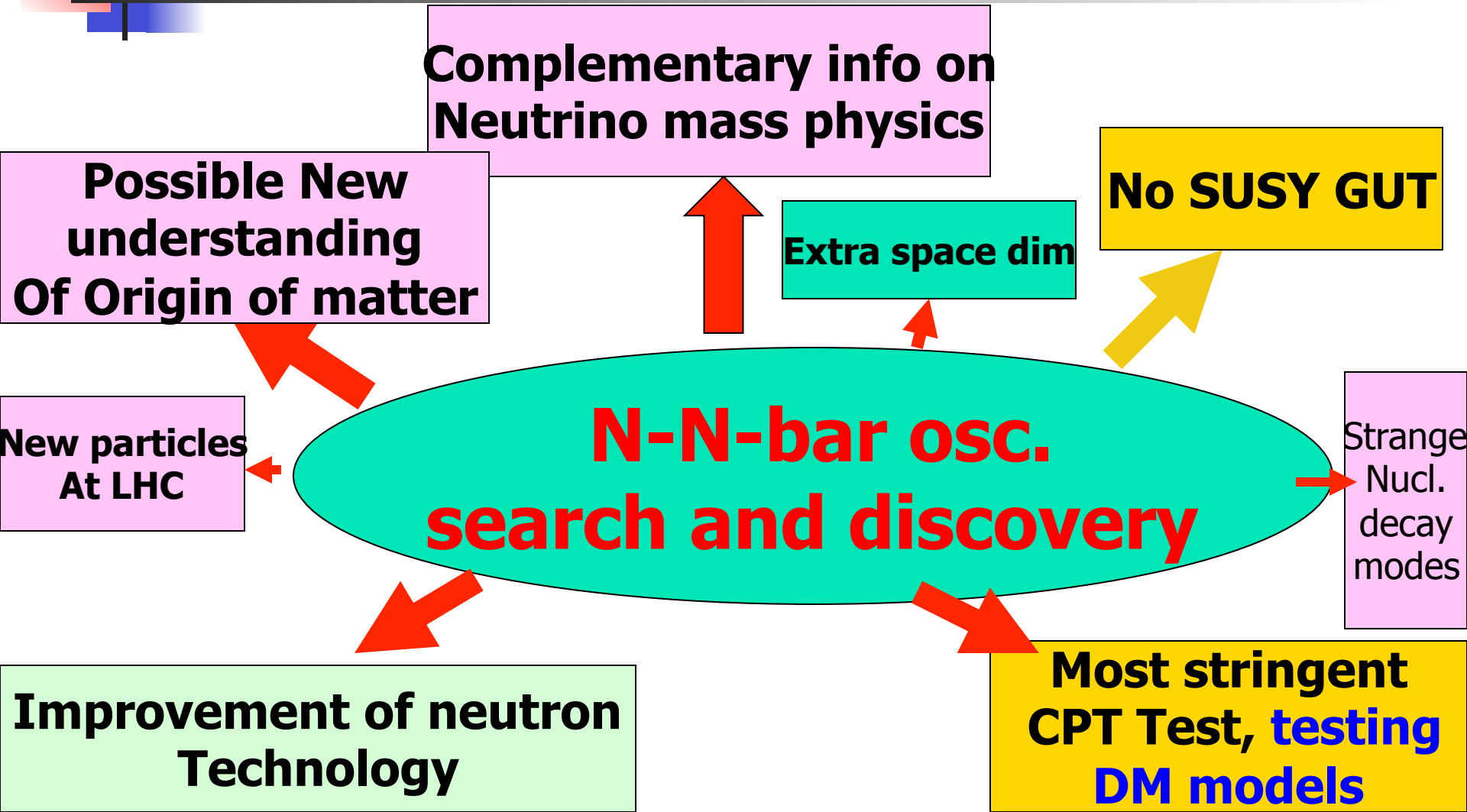
Zwirner (RPV), RNM, Valle (E_6); Babu, RNM; Goity, Sher;.



What else can we learn from direct NNbar search?

- Can test some dark matter hypothesis e.g. if a dark neutron n' is dark matter (ADM models):
- $n' \Leftrightarrow n$ oscillation can deplete dark matter density and this can be searched for in direct nn-bar searches; current limit > 1 s. **(Bento, Berezhiani)** (possibly a signal ?)
- If NNbar is discovered, it will put the strongest limit on CPT violation- **(Okun; Addazzi, BLV2011)**

NN-bar oscillation- gold mine of new physics info– 10^{11} sec. benchmark goal

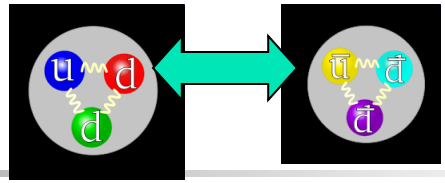


Predictions vs Discoveries: A historical perspective

Process	Predicted ?	Implications of non-discovery
CP Violation	No	nothing
m_c, m_b, m_t	No	a lot
W, Z	Yes	a lot
P decay $p \to e^+ + \pi^0$	yes $\tau \geq 10^{35}$ yrs	GUT idea in trouble
$p \to K^+ \bar{\nu}$	No	Nothing

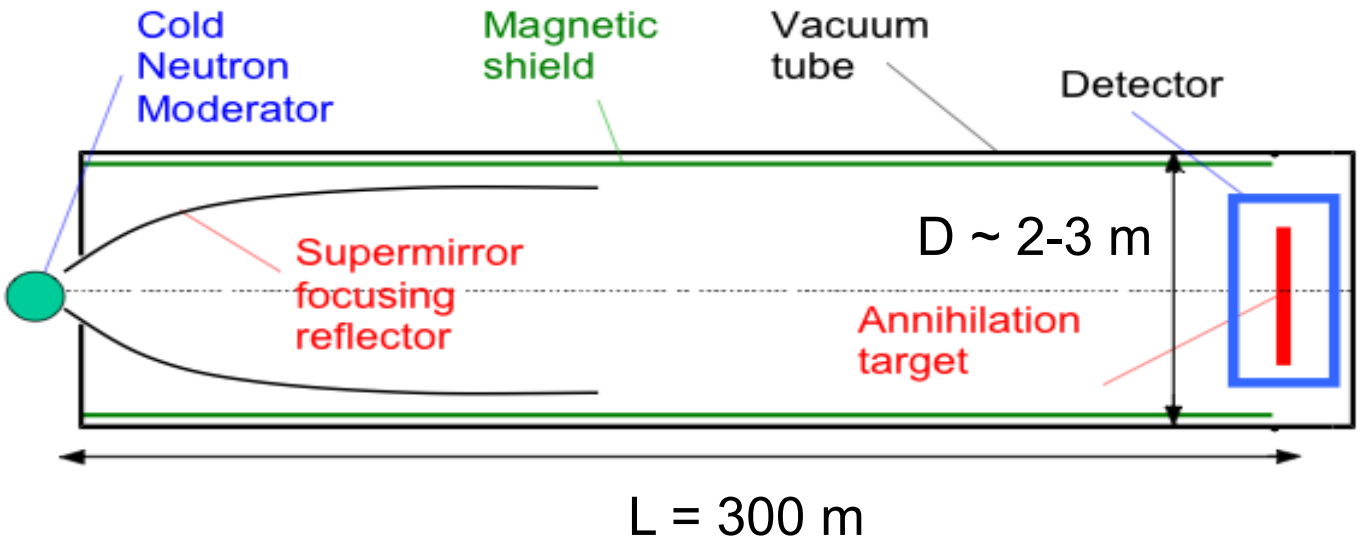
Thank you for your attention !

Search for N-N-bar Osc. current status



- **Free neutron oscillation in reactors: generic setup**

(talks by Snow, Young)



- **Current bound (ILL'94)**

with $L \sim 90$ m and $\langle t \rangle = 0.11$ sec

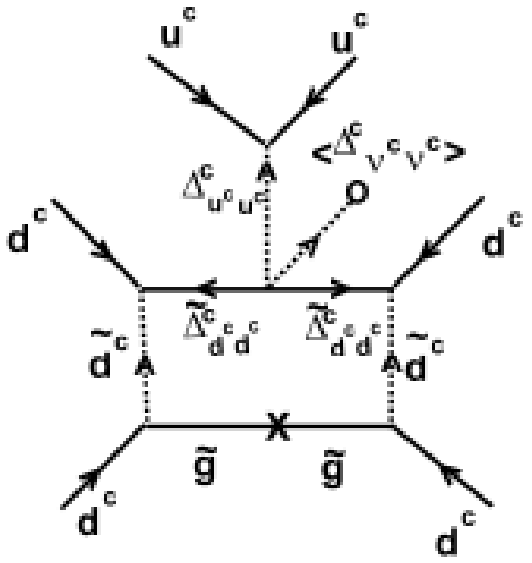
measured $P_{n\bar{n}} < 1.6 \times 10^{-18}$

$\tau > 8.6 \times 10^{7}$ sec

- **No new search after that**

Estimate of N-N-bar with susy

- **New Feynman diagram for N-N-bar osc.**



☞ $G_{N-\bar{N}} \simeq \frac{f^3 \Lambda}{\lambda^2 M^2_{seesaw} v^2_{wk}}$

$M_{seesaw} \sim 10^{11}$ GeV, typical f, λ, $\tau_{N-\bar{N}} \sim 10^{10}$ sec.

Observable N-N-bar osc for M_seesaw~10^11 GeV.

(Dutta, Mimura, RNM; PRL (2006)

Expectation for neutron-anti-neutron oscillation

- B-L violation at GUT scale leads to couplings

$$v_{BL}\Delta_{ud}\Delta_{ud}\Delta_{dd}$$

- → $G_{nn\text{-}bar} = \frac{v_{BL} f^3}{M^4_{\Delta_{ud}} M^2_{\Delta_{dd}}} = 10^{-29}\ GeV^{-5}$ →

$$\tau_{n\bar{n}} \sim \frac{G_{n\bar{n}}}{\Lambda^6_{QCD}} \sim 10^{10} sec.$$

- Observable with available reactor fluxes

From Seesaw to NNbar: a group theoretic argument

- Seesaw→ $\Delta L = 2$
- Scale not M_{Pl} suggests new gauge sym (B-L)
- → $Q = I_{3L} + I_{3R} + \frac{B-L}{2}$

$$\Delta Q = 0; \Delta I_{3L} = 0 \rightarrow \quad \boxed{\Delta I_{3R} = -\Delta \frac{B-L}{2}}$$

- For hadrons only, → $\Delta B = 2$ N-N-bar oscillation

Origin of matter and NNbar: TeV QL unif model

- Observation of NNbar will completely alter our thinking about the origin of matter.
- TeV QL model: NNbar transition in equilibrium 100 GeV

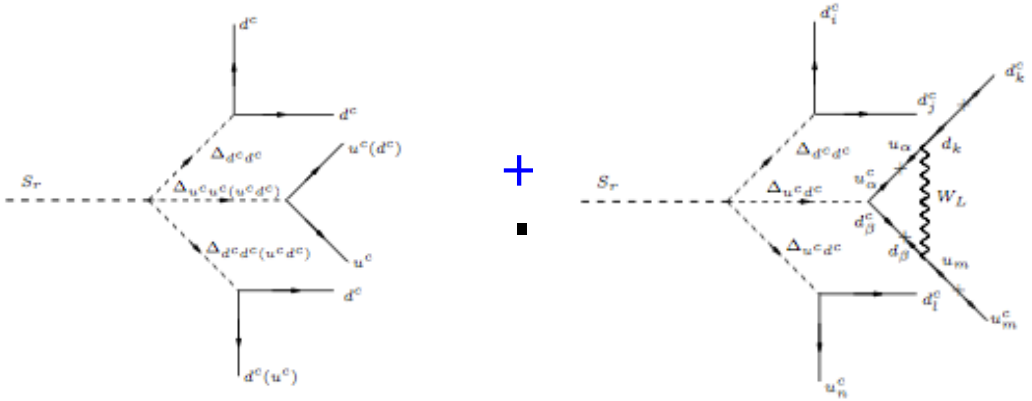
  ⇒ will erase any pre-existing matter asym !!
- New way to create matter below electroweak scale:

  Six quark NNbar operator

  coupled to a scalar fie

  (Post-sphaleron Baryogenesis)

  (Babu, RNM, Nasri' 07)



Low scale NNbar model and origin of matter

- Constraints on PSB in the $SU(2)_L x SU(2)_R x SU(4)_c$ model

i) $M_{\Delta_{qq}} > M_S$

ii) $1\ GeV < T_{S-decay} < 100 GeV$

iii) $\Gamma_{S\to 6q} > \Gamma_{S\to Z q\bar{q}}$

iv) A neutrino mass fit+FCNC constraints

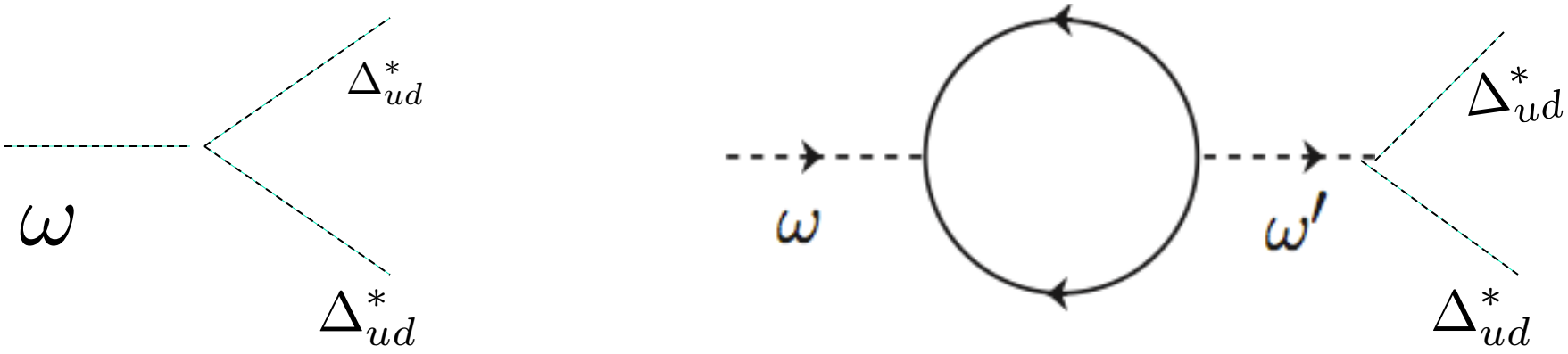
- For a v_{B-L} < 50 TeV, these constraints upper bound NNbar transition time < 10^{10} sec.
- **No NNbar till 10^{10} s., will rule out this model for post sphaleron baryogenesis and NNbar oscillation if v_{BL} < 50 TeV** (Babu,Dev,RNM'PRD'09; also B. D. M. Snow to appear.)

Origin of matter in SO(10) theory with NNbar

- Two sources of matter asymmetry:

  (a) Leptogenesis

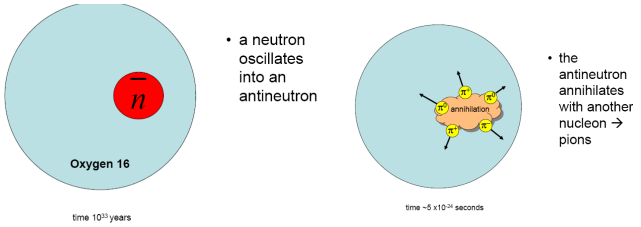
  (b) B-L violating GUT scale by $\Delta_{dd}(\omega)$ decay



- Must occur above T_{sph}~10^{13}-10^{12} GeV, below sphalerons are in eq. - ΔL must be out of eq. by T_{sph}

NNbar from di-nucleon decay

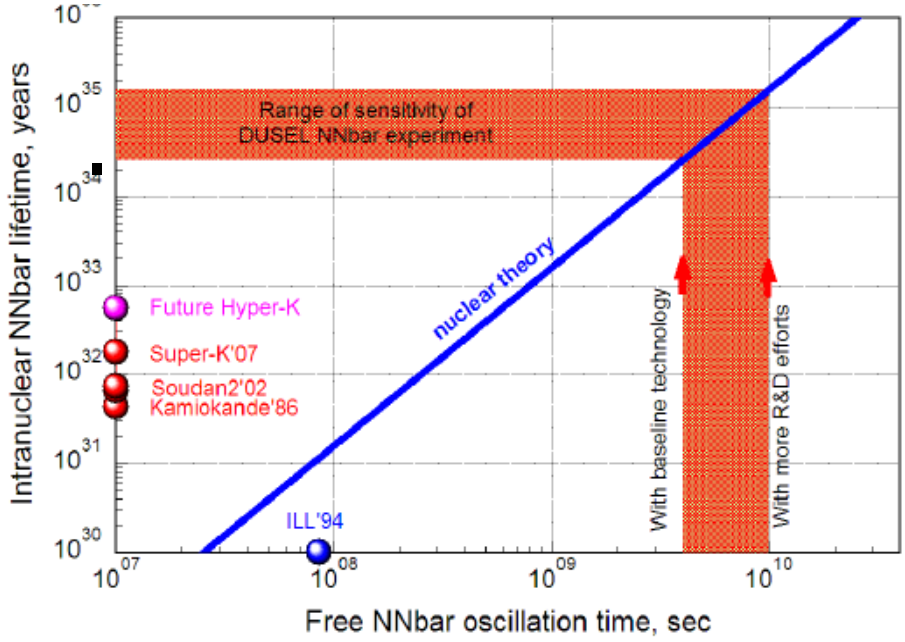
- Nucleon decay expts search for NNbar by looking for NN→$\pi's$ in a nucleus (Dover, Gal, Richards; Gal; Vainstein's talk)



$$\tau_{Nuc} = R\tau^2_{free}$$

$$R = 0.3\times10^{23}\ \text{sec}^{-1}$$

(Plot by Y. Kamyshkov)



$\tau_{n\bar{n}} > 2.44\text{x}10^8$ sec. (S-K,Abe et al.)

- Free oscillation search much more effective !!

Unique way to test GUT scale seesaw

- A natural scale for seesaw is GUT scale and is certainly required if forces and matter unify !!

- Without susy, no way to test such theories except for NNbar oscillation or B-L violating nucleon decays.